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HIGH-ENERGY FUELS FOR  
SUPERSONIC TRANSPORT RESERVES

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*Cleveland, Ohio*



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**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

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# HIGH-ENERGY FUELS FOR SUPERSONIC TRANSPORT RESERVES

by Joseph D. Eisenberg

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## SUMMARY

The reserve fuel requirements of the supersonic transports are expected to be about 10 percent of the gross weight of the aircraft, an amount approximately equal to that of the payload consisting of both passengers and baggage. This analysis shows that the reduction in the reserve fuel resulting from the use of high-energy fuels leads to significant increases in payload and reductions in direct operating costs. Since high-energy fuel is used only for reserves (common fuels such as JP fuel or kerosene, for example, continuing to be the primary fuel), which are expended infrequently, such costly fuels as liquid hydrogen and ethyldecaborane may be considered. The basic aircraft used in this study is arrow-winged, JP-fueled, has a constant takeoff gross weight of 460 000 pounds, and flies a constant range of 3500 nautical miles. The high-energy fuels used for the reserves are liquid hydrogen, ethyldecaborane, and liquid methane. One case of liquid hydrogen reserves in a methane-fueled supersonic transport, and one case of ethyldecaborane reserves in a JP-fueled aircraft operating at extended range are also investigated.

The results are presented as a function of the fraction of main-fuel reserve energy replaced by high-energy fuels. The sensitivity of the results to fuel-system weight is shown, and the direct operating costs are given for a spectrum of fuel prices.

For aircraft designed to use the high-energy reserves on the design range mission, the gains made with liquid-hydrogen reserves in the basic JP aircraft are the most interesting. The calculated direct operating cost improvement is nearly 10 percent and, associated with it, is a gain in passengers of over 15 percent when compared with the all-JP-fueled aircraft. If ranges in excess of the aircraft design range are required, the decrease in number of passengers and the increase in direct operating cost that results may be reduced by the use of ethyldecaborane in the JP supersonic transport. However, this possible gain does not include any adverse effects on engine performance due to boric oxide deposits.

## INTRODUCTION

Current supersonic transport designs use JP or kerosene fuel. There are, however, several fuels with much higher heating values than the JP fuels. A graphic example is liquid hydrogen, which has about three times the heating value. The higher the heating value and, therefore, the specific impulse, the lower the weight of fuel that is needed for a given propulsion energy requirement, and thus, a higher heating value fuel will generally yield a larger payload. Unfortunately, the higher heating value fuels usually have a higher cost, and thus, although the payload may increase, the cost per passenger may also increase. This increase in cost per passenger rules out the use of the high-energy fuels as the mission or cruise fuel for commercial aircraft.

High-energy fuels can be used advantageously, however. When the weights of any of the supersonic transport designs are examined, the weight of the reserve fuel is observed to be comparable to the weight of the passengers. Much of the reserve fuel is seldom used, and when it is not consumed, it is essentially dead weight which has, in a sense, merely displaced a sizeable number of passengers. Because part of the reserve fuel is infrequently used, a high energy, but high-cost fuel, may be utilized by replacing part of the reserves with it. By making the specification that all JP-fuel reserves are to be consumed prior to using the high-energy fuel, the weight savings is made, and the effects of the high cost of the high-energy fuel are minimized. This concept and its application to supersonic transports was originally suggested by Roger W. Luidens of the Lewis Research Center. This principle is particularly applicable to supersonic transports since the ratio of reserve weight to payload weight is higher than for present subsonic jet aircraft.

In addition to a high cost, some of the high-energy fuels have low densities that increase the tankage weight, and low boiling points that increase the weights of insulation. These weights decrease the potential gains. Only a mission study can determine the existence and size of the net gains.

This report analyzes the effect that the use of high-energy reserves has upon the payload capacity (the number of passengers) and the direct operating cost of a hypothetical four-engine arrow-wing supersonic JP-fueled transport with a fixed takeoff gross weight of 460 000 pounds, flying a range of 3500 nautical miles with a cruise speed of Mach 3. Ethyldecaborane, methane, and liquid hydrogen are considered as reserve fuels. One case of liquid hydrogen in a methane supersonic transport and one case of ethyldecaborane in a JP supersonic transport operating at extended range are also investigated. A statistical analysis is used to determine the average amount of reserve fuel used. The effect of a change in reserve fuel on major fuel system components, aircraft aerodynamics, and aircraft structures is accounted for.

The aircraft performance and economics calculations in this study are based on the

information presented in reference 1, which, in turn, was based on the large amount of data generated by the airplane industry during the current supersonic transport development program. The basic configuration as specified in reference 1 is similar to the SCAT 15F vehicle proposed by the NASA Langley Research Center, who provided the necessary aerodynamic data.

## SYMBOLS

$A$	area of tank, $\text{ft}^2$
$c_p$	specific heat, $\text{Btu}/(\text{lb})(^\circ\text{R})$
$F_A$	aircraft fuel system fraction (total weight of aircraft fuel systems/total weight of aircraft fuels), $(F_{t,h}W_{F,h} + F_mW_{F,m})/(W_{F,h} + W_{F,m})$
$F_h$	basic high-energy fuel system fraction (fuel system weight for high-energy fuel/weight of high-energy fuel), see eq. (4)
$F_m$	basic main fuel system fraction (weight of main fuel system/weight of main fuel)
$F_{t,h}$	total high-energy fuel system fraction $[F_h + (\text{additional fuel system weight for high-energy fuel/weight of high-energy fuel})]$
$I$	specific impulse, sec
$k$	insulation conductivity, $\text{Btu}/(\text{ft})(\text{hr})(^\circ\text{R})$
$L/D$	lift-to-drag ratio
$P$	probability of fuel use greater than $w$
$p$	distribution function of fuel use $w$
$\Delta T$	difference in temperature
$t$	thickness
$V$	aircraft cruise velocity
$W_F$	weight of fuel
$W_{MF}$	weight of mission fuel
$\Delta W_F$	weight of fuel required in excess of $W_{MF}$
$w$	$\Delta W_F/W_{MF}$
$\bar{w}$	average $w$
$\rho$	density, $\text{lb}/\text{ft}^3$

$\tau$  time

Subscripts:

co arbitrary cutoff

F fuel

h high energy

i insulation

m main

o refers to point of high-energy substitution

r reserve

S structure

s available for heat sink (referring to temperature)

t total

## METHOD OF ANALYSIS

In order to evaluate the effects on payload and direct operating costs resulting from the use of high-energy fuels for reserves, a representative supersonic transport and a representative mission are chosen. This transport and mission are the same as the basic aircraft and mission of reference 1. Modifications to the basic aircraft are made when required by fuel and payload changes. The standard equations of motion and aerodynamics are employed in the calculations. Since, in this study, the only changes are in the fuels burned, only the assumptions affecting the fuel system are discussed in detail.

### Mission and Reserves

The basic mission is outlined in table I, and a flight profile in terms of Mach number and altitude is presented in figure 1. The Mach number and altitude coordinates are fixed in all cases until a speed of Mach 1 is reached. At higher Mach numbers the altitude is increased when necessary in order to keep sonic boom overpressures on the ground no greater than 2.0 pounds per square foot. After completion of the climb phase, Mach 3 cruise is initiated and flown at the altitudes determined by maximizing the Breguet Range (ref. 2), that is, maximizing the product  $(L/D)(I)$ . The total length of the flight is 3500 nautical miles, but in one case extended ranges are flown.

TABLE I. - MISSION REQUIREMENTS

Range, n mi	3500 (4030 s mi)
Cruise Mach number	3.0
Sonic boom overpressure limit, lb/ft <sup>2</sup>	
Climb	2.0
Cruise	1.5
Reserve requirements:	
Percent of mission fuel	7
Cruise to alternate airport at cruise altitude and Mach number, n mi	261
Mach 0.6 hold at 15 000-ft altitude, min	30

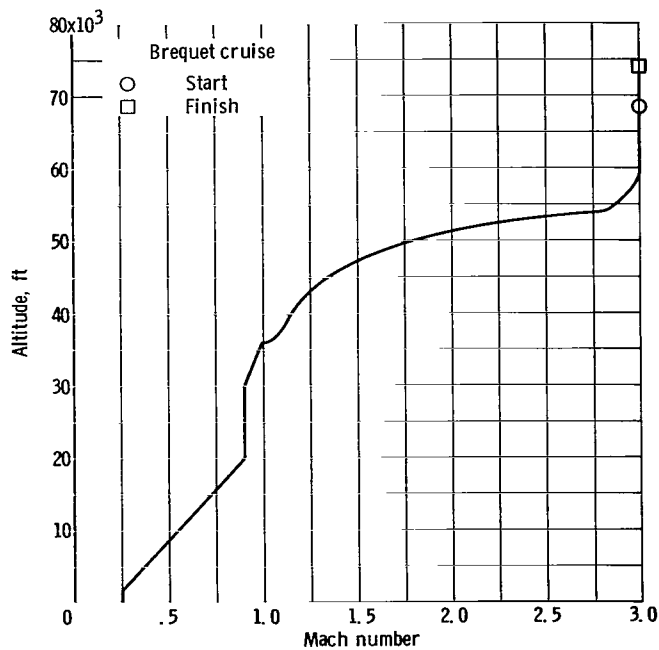


Figure 1. - Typical mission profile. Takeoff gross weight, 460 000 pounds; sonic boom overpressure limit, 2.0 pounds per square foot; takeoff gross weight per area of wing, 50 pounds per square foot.

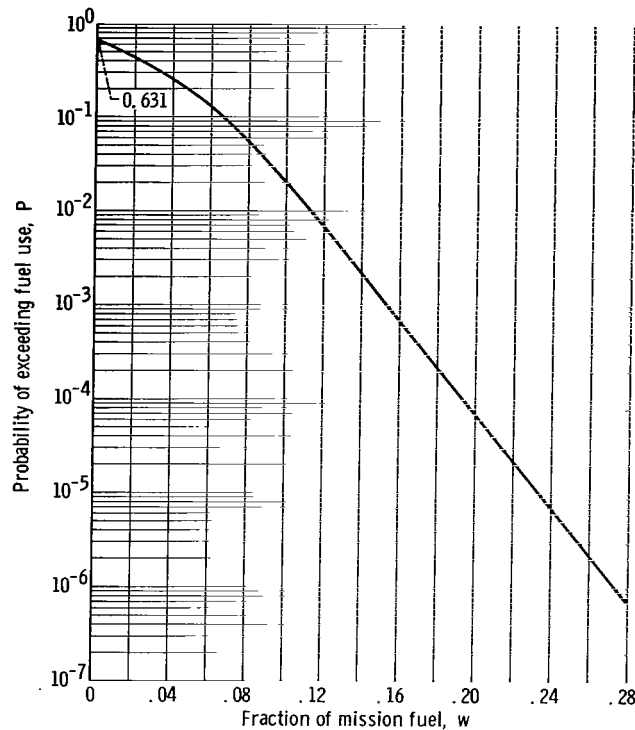


Figure 2. - Probability of reserve fuel use.

The amount of reserves, both main-fuel reserve and high-energy fuel reserve, expended per flight (when averaged over a large number of flights) must be known. These reserves are calculated by making use of a curve of probability of reserve fuel use (fig. 2). The abscissa is in terms of the ratio  $\Delta W_F / W_{MF}$  where  $W_{MF}$  is the amount of fuel required just to perform the planned mission (i. e., predicted wind, predicted atmospheric conditions, and no holding or flying to alternate airfields), and  $\Delta W_F$  is the weight of fuel required in excess of  $W_{MF}$  to perform the real mission. The ordinate  $P$  is the probability of requiring more than a given fraction of excess fuel. This curve is based on the probability curve presented in reference 3, which is based on experience with present-day long-range jet transports and adapted to supersonic transports. This figure shows that the frequency of use of the reserve drops off rapidly as  $\Delta W_F / W_{MF}$  increases. For example, 63.1 percent of all flights require more than the nominal fuel load to complete the mission. An additional 10-percent fuel load, however, is adequate for all except 2 percent of the flights. On the average flight, about 11 percent of the reserve energy is consumed.

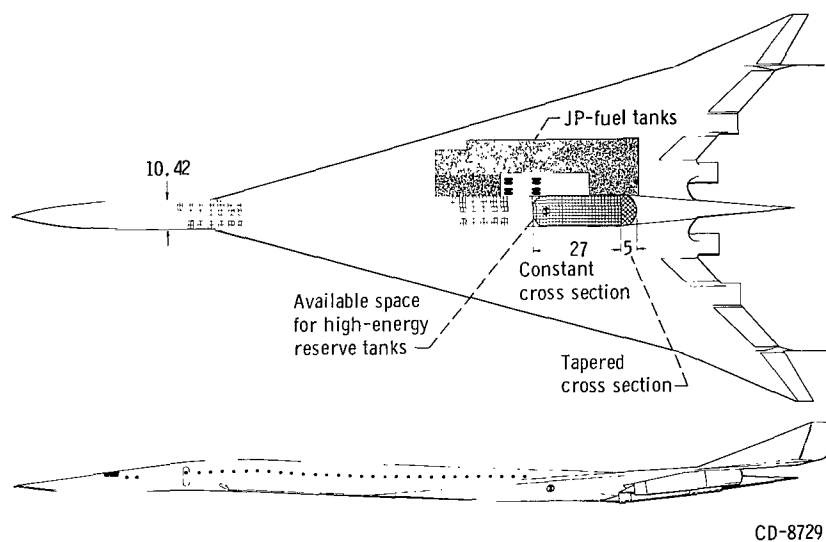
The actual amount of fuel carried by a supersonic transport that is allotted for reserves is calculated from the nominal requirements listed in table I, which are specified in reference 4. Changes in the rules concerning reserves have been made by the



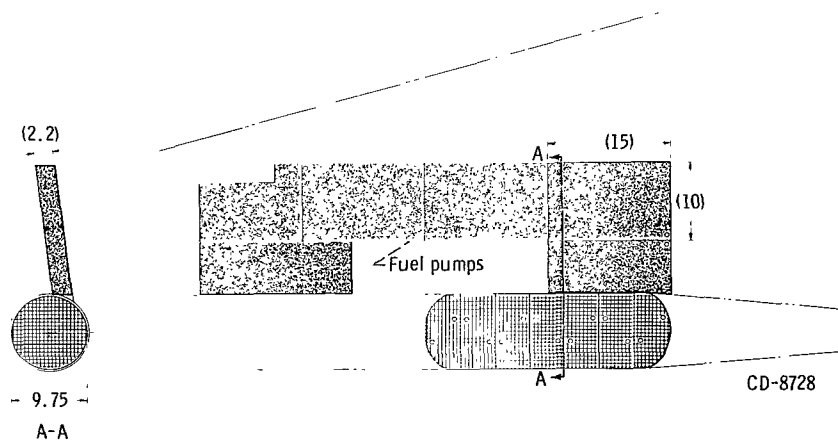
Federal Aviation Agency from time to time, but these rules are typical for the supersonic transport.

## Aircraft

The aircraft used are supersonic transport engine-airframe combinations consistent with reference 1. The aircraft configuration and characteristics, as presented in figure 3 and table II, respectively, are very similar to the SCAT 15F of the NASA Langley



(a) Overall view.



(b) Section detail of tank configuration. (Numbers in parentheses are typical dimensions.)

Figure 3. - Layout of 203-passenger all JP-fuel supersonic transport. (All dimensions are in ft.)

TABLE II. - AIRCRAFT CHARACTERISTICS

Wing planform area, ft <sup>2</sup>	9200
Aspect ratio	1.71
Fuselage outside diameter (max.), in.	125
Fuselage length, ft	243
Seat pitch, in.	34
Number of seats abreast	5
Engine design airflow, lb/sec	470

Research Center. The SCAT 15F and the basic aircraft of this study are both four engine, advanced, fixed-sweep, arrow-wing, supersonic transport configurations. The aerodynamic performance is based on data supplied by the Langley Center. The resulting cruise lift-to-drag ratio for the study aircraft is about 9.2 (ref. 1).

The aircraft has a constant takeoff gross weight of 460 000 pounds and a constant wing loading throughout this study. The wing area and the wing weight are thus constant. Each passenger has a weight of 200 pounds including baggage, and 116 pounds of furnishings are required per passenger. The fuselage length varies with the number of passengers, and with the fuel volume in some cases. The variation of fuselage weight with length is presented in figure 4. The length increase for passengers is determined by the 34-inch seat pitch and the 5 abreast seating as noted in table II. The increases in fuselage length required to accommodate the high-energy reserve fuel are presented in figure 5.

In connection with this fuselage increase, note that the basic JP-fueled supersonic

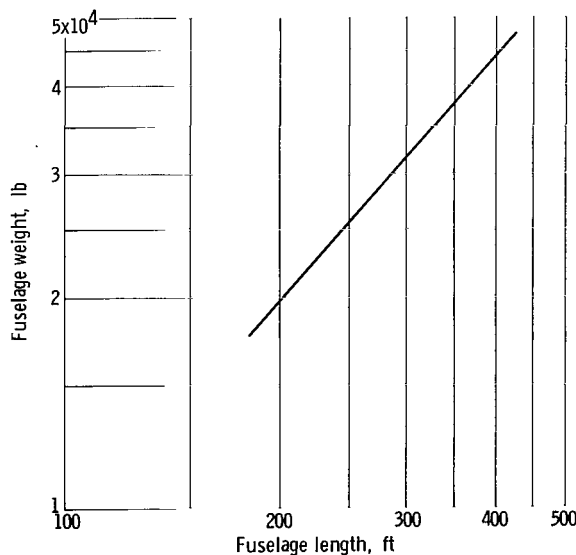


Figure 4. - Variation of fuselage weight with length.

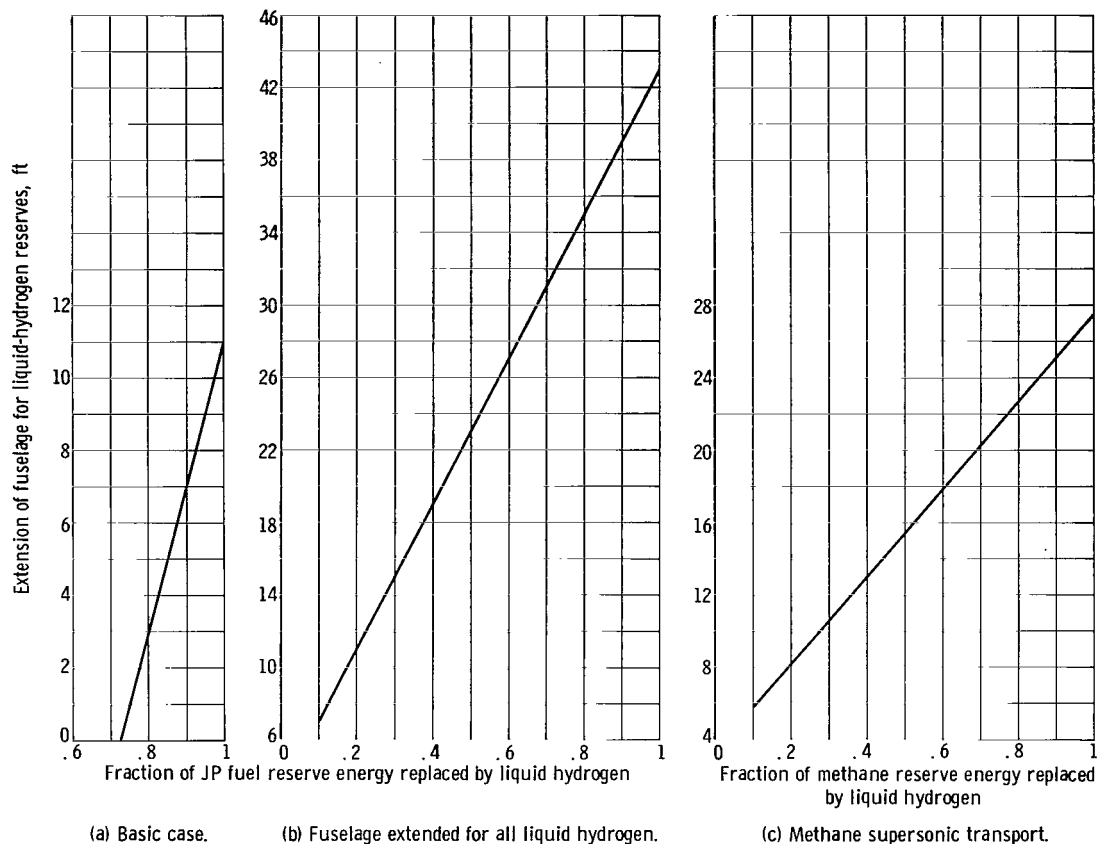


Figure 5. - Extension of fuselage for liquid-hydrogen reserves.

transport shown in figure 2 (p. 6) has a 27-foot-long section of constant cross section fuselage and a 5-foot section of tapered fuselage available for fuel storage. The empty fuselage space, like the empty space in the wing, results from the fact that the internal volume of the supersonic transport is determined by aerodynamics and associated engineering considerations and not only by the volume of the fuel and payload that is to be contained within it. Figure 5(a) presents the fuselage extension required by the JP-fueled supersonic transport with liquid-hydrogen reserves when 32 feet is available for fuel storage. Figure 5(b) differs from figure 5(a) in that the 32 feet is assumed unavailable for liquid hydrogen storage. Figure 5(c) is for a supersonic transport with methane mission fuel and liquid-hydrogen reserves.

The engine assumed for this study is an afterburning turbojet. The takeoff thrust-to-weight ratio and the aircraft takeoff gross weight are fixed, thus the size of the engines is fixed also. The characteristics of the engine are listed in table III. The engines operate without afterburning until a speed of Mach 1 is reached at about 36 000 feet altitude, full afterburning throughout essentially the entire supersonic acceleration region, and

TABLE III. - ENGINE CHARACTERISTICS

Number and type	<sup>a</sup> 4
Design compressor pressure ratio	10
Design turbine inlet temperature, °F	2100
Maximum compressor bleed air for turbine cooling, percent	6.6
Maximum afterburner temperature, °F	3000
Design compressor efficiency	0.875
Turbine efficiency	.88
Primary combustor efficiency	.98
Augmentor combustor efficiency	.93
Inlet pressure recovery at Mach 3.0	0.850
Engine design airflow, lb/sec	470

<sup>a</sup>Afterburning turbojets.

TABLE IV. - WEIGHT BREAKDOWN FOR

## SUPERSONIC TRANSPORT WITH

## ALL JP FUEL

Fuel weight, lb:	
Takeoff and climb	60 304
Cruise	101 810
Letdown	5 223
Reserves	34 454
Total fuel weight	201 791
Component weight, lb:	
Wing and verticle stabilizers	82 879
Fuselage	24 842
Installed engines	44 641
Fuel system	4 217
Landing gear	20 056
Hydraulic and electrical system	6 831
Surface controls	4 007
Passengers and baggage	40 600
Furnishings, electronics, passenger services, crew, crew baggage, emergency equipment, air conditioning, etc.	30 136
Takeoff, gross weight	460 000

TABLE V. - FUEL CHARACTERISTICS

Characteristic	JP fuel	Ethyldecaborane	Methane	Liquid hydrogen
Lower heating value, Btu/lb	<sup>a</sup> 18 600	<sup>a</sup> 26 450	<sup>b</sup> 21 000	<sup>c</sup> 49 900
Density, lb/ft <sup>3</sup>	50	52	26	4.4
Typical cost, \$/lb	0.01846	2.00	0.01846	0.50
Relative specific impulse, $I_h/I_m$	1.00	1.23	1.12	2.70
Boiling or decomposition point at 1 atmosphere, °R	810	660	201	37
Freezing point at 1 atmosphere, °R	375	445	164	25
Specific heat of liquid, $c_p$ , Btu/(lb)(°R)	0.47	0.7	0.82	1.75
References	1 and 9	7, 8, and 9	1, 9, and 10	5, 6, 9, and 10

<sup>a</sup>At 536.7° R.

<sup>b</sup>At 201° R.

<sup>c</sup>At 36.7° R.

partial afterburning during Mach 3 cruise in order to satisfy the maximum Breguet range condition.

A weight breakdown for the basic JP-fueled aircraft flying the basic mission is presented in table IV. Note that the weight of reserves is 34 400 pounds, which is close to that of the total payload, passengers plus baggage. The fuel system weight is 2.09 percent of the total weight of fuel.

## Fuel Characteristics

The fuels considered are JP, liquid hydrogen, ethyldecaborane, and liquid methane. The JP fuel is the main fuel throughout the majority of this study. One case using methane as the main fuel is considered, however.

The characteristics of these fuels, which are taken from reference 1 and references 5 to 10 are listed in table V. All fuels considered have higher heating values in Btu per pound than does JP fuel as shown in table V.

Ethyldecaborane is a room-storable fuel that is slightly more dense than JP. The combustion products of ethyldecaborane include boric oxide, a viscous solid that has been found to reduce drastically the performance of turbojet components. However, such losses are ignored in the present study. Methane and liquid hydrogen are cryogenics, methane having about one-half the density of JP fuel and liquid hydrogen having about one-twelfth the density of JP fuel. The costs of the high-energy fuels are, in general, greater than the cost of JP fuel.

Although the actual change in engine performance for different fuels is a function not only of fuel but also of flight conditions, calculations based on real gases using the tables and methods of reference 9 indicate typical relative values of specific impulse  $I$  which will be applied to all engine conditions in this study. Implicitly assumed in these calculations are the assumptions that the engines operate with unchanged component efficiencies and net thrust when fuel is changed, and that dual fuel system components are provided when required to allow inflight changing of fuel. The resulting ratios of the high-energy fuel specific impulse to that of JP fuel are listed in table V.

From high specific impulses, all gains are derived; for the higher specific impulse means less weight of fuel required. A first approximation of the weight of high-energy reserves required is given by the relation

$$W_{F,h,r} = W_{F,m,r} \frac{I_m}{I_h} \quad (1)$$

where  $W_{F,h,r}$  is the high-energy reserve weight required to replace a weight of main-reserve fuel  $W_{F,m,r}$ ; and  $I_m$  and  $I_h$  are the main and high-energy specific impulses, respectively. In the actual performance calculations of this study, however, the changes in mission and reserve energy requirements resulting from the changes in the aircraft from case to case are taken into account.

## Fuel System

Basic relation. - The fuel system related weights for the JP supersonic transport may be conveniently divided into two sections. The first is the engine portion, which consists of such items as engine fuel pumps and engine fuel controls and is considered a part of the engine weight. Although changes in reserve fuel will force some modifications, the expected weight changes are small, and therefore, these engine changes are neglected in this study. The second portion is the aircraft fuel system, which consists of the following items:

Basic fuel system (all fuels including cryogenics):

Pumps

Valves

Fuel lines and supports

Miscellaneous plumbing

Electrical components

Heat exchangers

Tank walls, baffles, sealant

Additional fuel system (only for cryogenic fuels):

Insulation

Pressure structure

The basic fuel system is required for both the storable and cryogenic fuels. The additional fuel system is only required for cryogenic fuels.

The additional fuel system weight for high-energy fuels may consist of an insulation weight and a structural weight depending on the particular fuel. Using the definition for  $F_{t,h}$  (the total fuel system fraction for the high-energy fuel) results in the following expression (see SYMBOLS):

$$F_{t,h} = \frac{F_h W_{F,h} + W_S + W_i}{W_{F,h}} \quad (2)$$

where  $W_{F,h}$  is the weight of high-energy fuel and  $W_S$  and  $W_i$  are the weights of additional structure and insulation, respectively.



The aircraft fuel system fraction  $F_A$  then becomes, in terms of  $F_m$  and  $F_{t,h}$ ,

$$F_A = \frac{F_{t,h} W_{F,h} + F_m W_{F,m}}{W_{F,h} + W_{F,m}} \quad (3)$$

where  $W_{F,m}$  is the weight of main fuel. The quantities  $F_h$ ,  $W_S$ , and  $W_i$  are computed for each of the several high-energy fuels and for the varying amounts of these fuels carried. When these quantities are substituted into equations (2) and (3),  $F_A$  becomes a varying aircraft fuel system fraction dependent on the characteristics of the high-energy fuel and on the amount of reserve energy replaced by the high-energy fuel.

Computation of weights. - To determine accurately  $F_h$  and thus  $F_{t,h}$  would necessitate a complete detailed fuel system design including pumps, piping, and other similar components. This complete design is beyond the scope of this report. Herein an approximate method for determining these fractions is derived.

The high-energy fuel-system fraction  $F_h$  is determined from  $F_m$  by a scaling method based on the model shown in figure 6 (p. 14). In figure 6(a) a twelve tank JP fuel system is shown schematically. All tanks are assumed equal both in volume and in surface area. The fuel is pumped to the four engines from one tank at a time. The reserve fuel is contained in two of the tanks. In figure 6(b), one tank of JP reserve is replaced by liquid hydrogen. An amount of liquid hydrogen having the same energy as a given amount of JP although lighter in weight is about four times as voluminous. Therefore, four tanks are required. These reserve tanks themselves and all their components are assumed to be the same in size, geometry, and weight as those used for JP fuel. In this case, as presented in figure 6(b), pumping of liquid hydrogen to the engines is now done from all four tanks simultaneously; thus, pumps, lines, etc., associated with each tank handle the same volume of fuel as in the original JP case.

Although only a liquid-hydrogen reserve substitution was used in this example, this model can be applied to any fuel used for reserve substitution. With this model, the following relation for the determination of  $F_h$  results:

$$F_h = F_m \frac{\rho_{F,m}}{\rho_{F,h}} \quad (4)$$

where  $\rho_{F,m}$  and  $\rho_{F,h}$  are the density of the main fuel and high-energy fuel, respectively. This equation can be expected to give reasonable results when substantial quantities of the reserve fuel are replaced by high-energy fuels. This area is the one of interest because all significant gains in aircraft performance and direct operating cost occur when large substitutions of high-energy fuels are made. In this study, the  $F_m$  for JP

All-JP-fueled supersonic transport	
Component	Fraction of system weight
Pumps	0.00174
Valves	.00262
Fuel lines and supports	.00616
Miscellaneous plumbing	.00102
Electrical components	.00092
Heat exchangers	.00124
Tank walls, baffles, and sealant	.00720
Total	0.02090

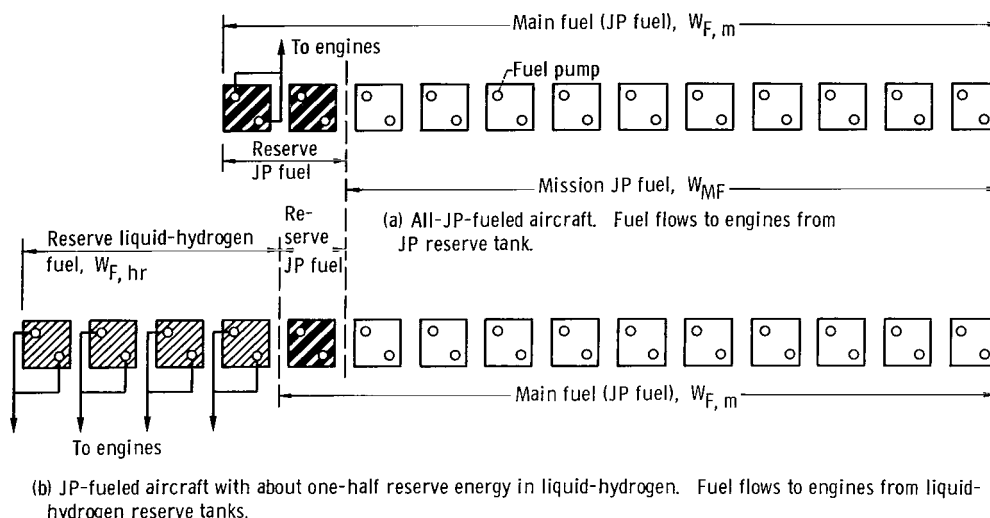


Figure 6. - Schematic of supersonic transport fuel system.

0.0209 (ref. 1). The fractional weights of the components making up this  $F_m$  are also presented in figure 6. For the one case in which methane is used for the main fuel,  $F_m$  is increased to 0.0396 (ref. 1). Both values for  $F_m$  are identical to those in reference 1. The values of  $F_h$  are computed based on these assumptions.

Note that the relation of equation (4) is used only for reserve systems and that it is possibly a bit conservative. The value of  $F_m$  used for the aircraft with methane as the main fuel is not obtained by raising the  $F_m$  for JP by the scaling methods presented herein. The 0.0396 value is from reference 1, and it results when either a heavy insulation or a methane vapor pumping system is used. This 0.0396 value is scaled up for the liquid-hydrogen reserves in order to push the  $F_h$  for liquid hydrogen in the conservative direction.

In using ethyldecaborane the value of  $F_A$  was assumed equal to that for JP, ethyldecaborane fuel being just slightly more dense than JP and also room storable. Since liquid hydrogen and liquid methane are cryogenic and since the boiling away of these fuels during the flight would defeat the purpose of their use as reserves, a system of pressurization, subcooling, and insulation is used that eliminates boiloff. The methane and liquid-hydrogen reserves are stored in the fuselage. The fuselage is designed to hold a pressure of no less than the 5000-foot altitude pressure of 12.2 pounds per



square inch absolute required for the passengers and crew, even at maximum altitude. Therefore, both the methane and liquid-hydrogen reserves are also stored at a pressure of 12.2 pounds per square inch absolute at altitudes above 5000 feet and at ambient pressure at lower altitudes.

At the beginning of the flight, the liquid hydrogen is cooled to  $27^{\circ}\text{R}$ , just two degrees above its freezing point, the lowest temperature that seems practicable. Sufficient insulation is then provided to allow a total heat leak throughout the flight so that the vapor pressure of the subcooled liquid will not exceed 12.2 pounds per square inch absolute. (The insulation thickness ranges from 8.5 to 3.0 in. as the fraction of reserve energy replaced by liquid hydrogen varies from 0.1 to 1.0). For the storage of the liquid methane, an insulation thickness of 1.5 inches is used throughout. This amount of insulation is more than sufficient to contain the fuel for the cases considered. The methane is then cooled below its sea level atmospheric pressure boiling temperature in order that the total heat leak allowed will raise the vapor pressure to no more than 12.2 pounds per square inch absolute upon landing. At the end of the flight, the heated fuel must be either recooled aboard the aircraft or off-loaded for recooling, and fuel already subcooled must be put aboard for the next flight.

An alternate method for handling cryogenic fuels that eliminates the problems of subcooling, such as pressurization and the off-loading, subcooling, and reloading of fuel is to load the fuel at its normal boiling condition into a tank capable of holding the 14.7 pounds per square inch absolute pressure. The fuel tank pressure is then maintained at 14.7 pounds per square inch absolute throughout the flight, and some boiling occurs due to heat leaks into the tank. The insulation thickness is selected so that the direct operating cost is minimized. Although this method is not used as the basic one in this analysis, an example with liquid hydrogen using this method is presented.

The equation used to determine the insulation thickness for subcooled fuel is

$$t_i = \frac{Ak(\Sigma \tau \Delta T)}{c_p \Delta T_s W_F} \quad (5)$$

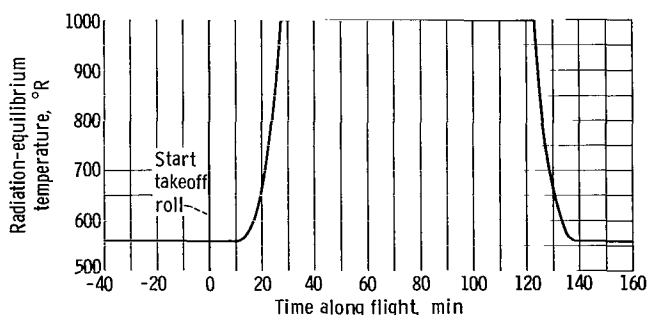


Figure 7. - Aircraft fuselage surface temperature as function of time along flight.

The weight of insulation  $W_i$  is then computed from the values of  $t_i$ ,  $\rho_i$ , and  $A$ . The radiation-equilibrium temperature for the fuselage exterior as a function of time along the flight is presented in figure 7. (The fuselage exterior is also the fuselage tank exterior.) The characteristics of the insulation used are presented in table VI (p. 16).

TABLE VI. - FUEL TANK INSULATION DATA

Insulation	Silica aerogel powder (ref. 13)
Insulation covering	High-temperature-resistant plastic film (ref. 14)
Insulation density, $\rho$ , lb/ft <sup>3</sup>	6
Insulation thermal conductivity, k, Btu/(ft)(hr)(°R)	0.0114
Air pressure within insulation, mm Hg abs	30 (0.58 psia)

A second pressurization bulkhead is added to each end of the fuselage tank when liquid-hydrogen is used in order to protect further against liquid-hydrogen leakage. The weight of the bulkheads  $W_G$  is 169 pounds.

Figure 3(b) (p. 7) indicates the assumed fuel system for this study. This fuel system is a multitank system very similar to the schematic model on which the fuel system scaling factors are based.

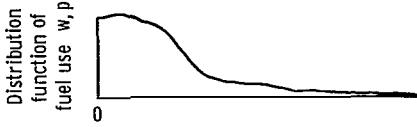
### Derivation of Reserve-Use Equations

From table IV (p. 10), the amount of reserve that is carried aboard the aircraft due to the requirements listed in table I (p. 5) is about 21 percent of the mission fuel. From figure 2 (p. 6), the probability of using more than this amount is  $4 \times 10^{-5}$ . Although the amount of reserve carried aboard the supersonic transport is calculated from the reserve requirements given in table I, it is not surprising that the amount of reserve fuel demanded by the requirements has only a small chance of being exceeded on any one flight, since both the probability curve and the reserve requirements of table I are based on experience with flying aircraft. The need for reserve fuel above that aboard the aircraft would not necessarily mean the loss of the craft. It would probably only mean the necessity of cutting short the mission and landing at an alternate location.

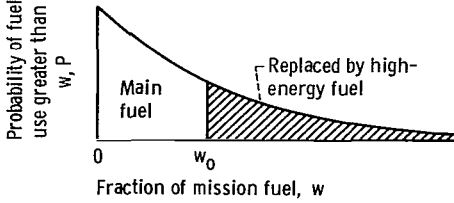
Using the information given in figure 2, a relation is developed for computing the average amount of main-fuel reserves and the average amounts of high-energy reserves consumed per flight. The stipulation is made that all main-fuel reserves are used prior to using any high-energy reserves.

The quantity  $\Delta W_F / W_{MF}$  is represented by  $w$  in this derivation. From reference 11, the average fraction of reserve fuel consumed  $\bar{w}$ , if only one kind of fuel and no fuel limitations are assumed, may be written

$$\bar{w} = \int_0^{\infty} wp \, dw \quad (6)$$



(a) Graphic representation of equation (6).



(b) Two-fuel situation.

Figure 8. - Distribution of fuel used against the fraction of reserve fuel consumed.

where  $p$  is the distribution function for  $w$  the fraction of fuel being used. This is represented graphically in figure 8(a).

Figure 8(a) shows that for any  $w$  the probability of using more than the fraction  $w$  is

$$P = \int_{\infty}^w p \, dw = - \int_w^{\infty} p \, dw \quad (7)$$

Thus, within this range

$$\frac{dP}{dw} = -p \quad (8)$$

and the average fraction for the reserve fuel consumed for the total range of  $P$  is from equations (6) and (8)

$$\bar{w} = - \int_{w=0}^{w=\infty} w \, dP \quad (9)$$

Graphically, the integral represents the area under the curve of  $P$  against  $w$  (fig. 2, p. 6).

Figure 8(b) illustrates the case of cutting the range of  $w$  into two parts at  $w_0$  to represent the two-fuel situation. The magnitude of  $\bar{w}$  for the main fuel only  $\bar{w}_m$  is the area under the curve from 0 to  $w_0$ . For this case, then, equation (9) becomes

$$\bar{w}_m = \int_{w=0}^{w=\infty} w(-dP) - \int_{w=w_0}^{w=\infty} (w - w_0)(-dP) \quad (10)$$

Equation (10) reduces to

$$\bar{w}_m = \int_{w=0}^{w=w_0} w(-dP) + w_0 \int_{w=w_0}^{w=\infty} (-dP) \quad (11)$$

The integral  $\int_{w=w_0}^{w=\infty} (w - w_0)(-dP)$  of equation (10), again with the assumption of no fuel limitation, represents the average weight fraction of fuel to the right of  $w_0$  that would be used if it were still in main fuel. To determine the average weight fraction of high-energy fuel used  $\bar{w}_h$  it is only necessary to multiply this integral by  $I_m/I_h$ . Thus,

$$\bar{w}_h = \frac{I_m}{I_h} \left[ \int_{w=w_0}^{w=\infty} w(-dP) - w_0 \int_{w=w_0}^{w=\infty} (-dP) \right] \quad (12)$$

In the actual situation, the reserve fuel is not infinite. There is sufficient reserve fuel, however, so that an arbitrary cutoff  $w_{co}$  can be chosen in the area where fuel is still available. This cutoff results in negligible errors in the computation of the fractional amount of high-energy fuel consumed. This  $w_{co}$  is used as the upper limit. The computations were actually done by summation. Using  $w_{co}$  as the upper limit and the form in which the calculations were accomplished yield the following working equations:

$$\bar{w}_m = \sum_{w=0}^{w=w_0} w \Delta P + w_0 \sum_{w=w_0}^{w=w_{co}} \Delta P \quad (13)$$

and

$$\bar{w}_h = \frac{I_m}{I_h} \left( \sum_{w=w_0}^{w=w_{co}} w \Delta P - w_0 \sum_{w=w_0}^{w=w_{co}} \Delta P \right) \quad (14)$$

where  $\Delta P$  is used for the absolute value of  $-dP$ .

To get the actual weights of reserve fuel consumed,  $\bar{w}_m$  and  $\bar{w}_h$  of equations (13) and (14), respectively, are multiplied by  $W_{MF}$ .

### Computation of Aircraft Passenger Load

The basic fixed-gross-weight aircraft, as described previously, is flown by a computer program through the specific mission, which has also been discussed. Greater amounts of the high-energy fuel are substituted incrementally for main-fuel reserves with the necessary aircraft modifications being made in each case. The result is a series of aircraft fuel weights, system weights, and number of passengers. Thus, the payload, or number of passengers, as a function of type and amount of reserve fuel is obtained.

The following main cases are studied: the JP-fueled aircraft with liquid-hydrogen reserves, with ethyldecaborane reserves, and with methane reserves. All three main cases utilize the 32 feet of fuselage length that can accept fuel. One case is investigated for the JP-fueled aircraft with liquid-hydrogen reserves with the assumption that no

fuselage volume is available for fuel storage and that fuselage extension is required for all liquid-hydrogen additions.

Also, the methane-fueled aircraft of reference 1 is examined with liquid hydrogen for the reserve requirement, and the standard JP aircraft using ethyldecaborane for reserve only for flights of more than 3500 nautical miles is investigated.

TABLE VII. - SUMMARY OF

FUEL PRICES

Fuel	Price, dollars/lb
Main fuel	
JP	0.01846
Methane	0.01846
High-energy reserve fuel	
Liquid hydrogen	0.05, 0.25, 0.50
Ethyldecaborane	0.50, 1.00, 2.00
Methane	0.01, 0.02

## Computation of Direct Operating Costs

The economic value of changes in the aircraft is best shown by the direct operating costs. Included in the direct operating cost are the crew costs, fuel and oil costs, insurance costs, direct maintenance of flight equipment, and the depreciation of the aircraft. The direct operating costs are computed by the formulas of reference 12, where the required inputs are taken from reference 1 as follows: 118 dollars per pound for airframe, 1.33 million dollars per engine, and a time between overhauls for the engine of 2000 hours.

Since the future costs of high-energy fuels are uncertain, the high-energy fuels are studied over a spectrum of prices. The main fuels are kept constant in price, the JP-fuel price being assumed as 12 cents per gallon. A summary of prices used is shown in table VII.

## RESULTS

The results are presented as the number of passengers and the direct operating cost for various fractions of reserve-fuel energy replaced by high-energy fuel. All but the last section of this report considers aircraft that are designed to use high-energy reserves on the design range mission. Liquid hydrogen, ethyldecaborane, and methane reserves are considered in turn. The last section considers the use of ethyldecaborane reserves in a previously designed JP-fueled aircraft flying at a range extended beyond the design value. The complete results are presented graphically in figures 9 to 23 (pp. 22 to 33). A summary of the most important results is presented in tables VIII and IX (pp. 20 and 21, respectively).

TABLE VIII. - SUMMARY OF RESULTS USING STANDARD ASSUMPTIONS<sup>a</sup>

Main fuel	Reserve fuel	Parameter that fuel reserve change optimized	Aircraft fuel system fraction, $F_A$	Fraction of reserve energy replaced by high-energy fuel	Number of passengers	Passenger increase fraction	Main fuel cost, cents/lb	High-energy fuel cost, cents/lb	<sup>a</sup> Direct operating cost	Savings of direct operating cost fraction
JP	JP	-----	0.0209	0.000	203	-----	1.846	---	1.072	-----
JP	Liquid hydrogen	Number of passengers	.0481	1.000	237	0.1675		---	-----	-----
JP	Liquid hydrogen	Direct operating cost	.0414	.760	231	.1379		50	.965	0.0998
JP	Liquid hydrogen	Direct operating cost	.0437	.845	234	.1527		25	.956	.1082
JP	Liquid hydrogen	Direct operating cost	.0481	1.000	237	.1675		5	.937	.1259
Methane	Methane	-----	.0396	.000	238	-----		---	.894	-----
Methane	Liquid hydrogen	Number of passengers	.0668	1.000	259	.0882		---	-----	-----
Methane	Liquid hydrogen	Direct operating cost	.0581	.700	252	.0588		50	.865	.0324
Methane	Liquid hydrogen	Direct operating cost	.0603	.750	253	.0630		25	.860	.0380
Methane	Liquid hydrogen	Direct operating cost	.0668	1.000	259	.0882		5	.843	.0570
JP	Ethyldecaborane	Number of passengers	.0209	1.000	217	.0690		---	-----	-----
JP	Ethyldecaborane	Direct operating cost	.0209	.520	210	.0345		200	1.043	.0271
JP	Ethyldecaborane	Direct operating cost	.0209	.525	210	.0345		100	1.041	.0289
JP	Ethyldecaborane	Direct operating cost	.0209	.560	210	.0345		50	1.037	.0326
JP	Methane	-----	.0264	1.000	209	.0296		---	-----	-----
JP	Methane	Direct operating cost	.0264	1.000	209	.0296		2	1.044	.0260
JP	Methane	Direct operating cost	.0264	1.000	209	.0296	↓	1	1.041	.0288

<sup>a</sup>Standard assumption: 32-foot length of fuselage available for fuel.

TABLE IX. - LONG-FUSELAGE JP FUELED SUPERSONIC TRANSPORT LIQUID-HYDROGEN RESERVES

[ No liquid-hydrogen storage space initially available in JP-fueled supersonic transport. ]

Parameter that fuel reserve change optimized	Liquid- hydrogen cost	Number of passengers	Number of passengers (standard assumption) <sup>a</sup>	Fuselage length, ft	Fuselage length, ft (standard assumptions)	Passenger decrement, passengers/ft	Direct oper- ating cost, cents/seat- statute-mi.	Direct oper- ating cost, savings fraction	Direct oper- ating cost, savings frac- tion (standard assumption)
Number of passengers	--	221	237	296	273	0.696	-----	-----	-----
Direct operating cost	50	214	231	280	260	.850	1.044	0.0270	0.0998
Direct operating cost	25	217	234	287	265	.773	1.034	.0354	.1082
Direct operating cost	5	221	237	296	273	.696	1.011	.0569	.1259

<sup>a</sup>Standard assumption: 32-foot length of fuselage available for fuel.

## Improvements Using Liquid Hydrogen

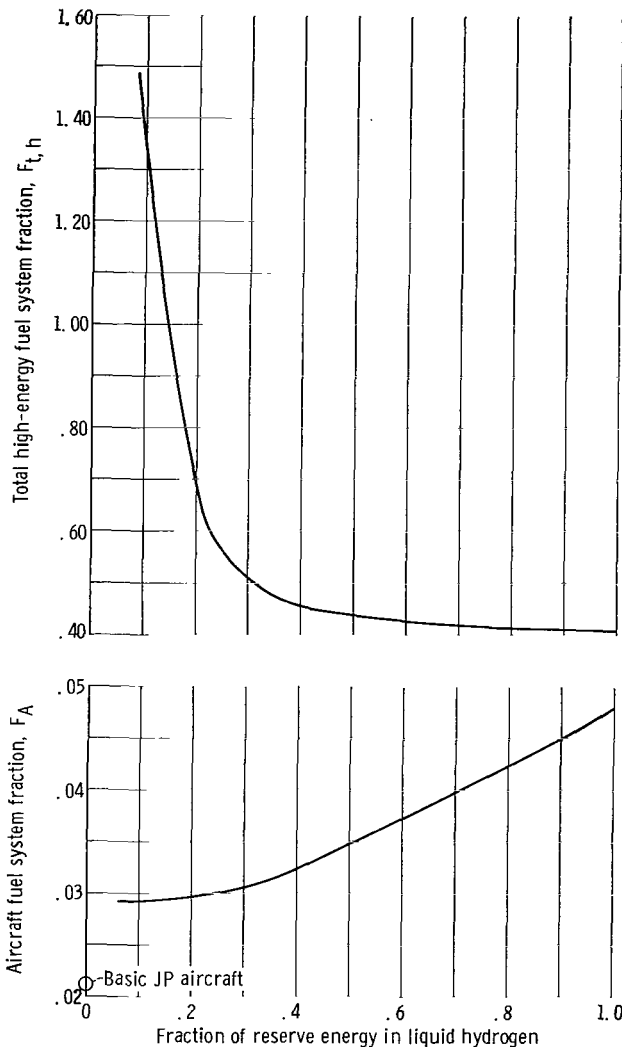


Figure 9. - Computed system fractions for JP-fueled supersonic transport with liquid-hydrogen reserves.

The initial case is that of liquid-hydrogen reserves in the basic JP-fueled supersonic transport. In this basic aircraft (fig. 3, p. 7), a 32-foot length of fuselage is available for liquid-hydrogen storage. All liquid-hydrogen is stored in the fuselage tanks, and when required, the fuselage is extended for this purpose, as shown in figure 4 (p. 8). The values for  $F_{t,h}$  and  $F_A$  used in these computations are shown by the curves in figure 9. The discontinuity between the basic JP aircraft system fraction and that of the hydrogen system fraction is due to the requirements for bulkheads, insulation, etc., required for even minute quantities of liquid hydrogen.

Figures 10 and 11 present the number of passengers and the direct operating cost, respectively, as functions of the fraction of reserve energy in liquid hydrogen. The curves based on the computed  $F_A$  in figure 9 (shown as solid lines) will be discussed for the most part. The other curves of higher

and lower  $F_A$  are added in order to indicate the sensitivity of the number of passengers and the direct operating cost to a change in the aircraft fuel system fraction.

The curves in figure 10 show that the maximum increase in passengers occurs when the liquid hydrogen replaces all the JP reserves although the fuselage is extended 11 feet for fuel and 19 feet for passengers and the  $F_A$  is more than doubled. Figure 9 shows that the  $F_{t,h}$  with all liquid-hydrogen reserves is 0.406 and that the  $F_A$  is 0.0481 for this maximum passenger case. The increase in passengers is 34, or a 16.75 percent increase. From the maximum points in the figure, it may be determined that a 0.01 change in system fraction  $F_A$  (which is equivalent to a 0.17 change in  $F_{t,h}$ ) results in a difference of four passengers. Thus, a sizable gain in passengers can be obtained even for quite high values of  $F_A$ .



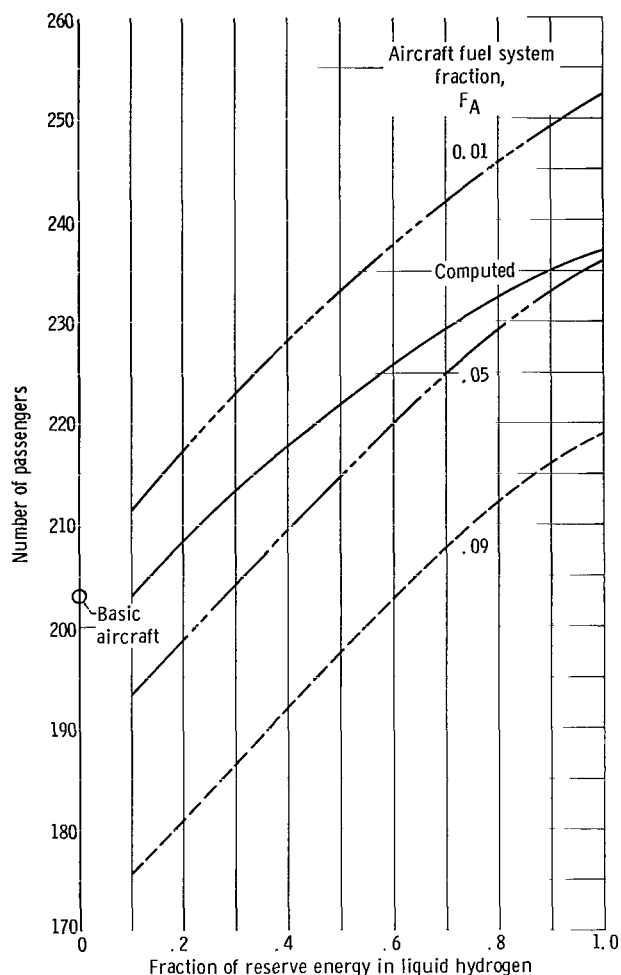


Figure 10. - Number of passengers for JP-fueled supersonic transport with liquid-hydrogen reserves.

In figure 11, the direct operating costs associated with the passenger gains are presented. The direct operating cost is in cents per seat per statute mile. Curves are plotted not only for several values of  $F_A$  but also for several prices of liquid hydrogen. The current cost of liquid hydrogen is about 50 cents per pound. The results using lower prices are included to show the sensitivity of direct operating cost to fuel price changes.

The curve based on the computed  $F_A$  shows that at the higher costs of liquid hydrogen, a minimum point on the curve exists, but at low liquid-hydrogen cost, total replacement of reserves by liquid hydrogen gives the best result. It may be computed from the minimum direct operating costs that at 50 cents per pound for liquid hydrogen, the reduction in direct operating cost is about 10 percent, and at 5 cents per pound, the savings have risen slightly to 12.6 percent. These are both significant gains, and their closeness demonstrates that, in the case of liquid-hydrogen reserves in a JP aircraft, the high price of hydrogen does not make its

use appear much less attractive. If minimum points of direct operating cost for varying  $F_A$  are compared, the determination may be made that a 0.01 increase in  $F_A$  (0.17 in  $F_{t,h}$ ) would cause about a 20 percent reduction in direct operating cost savings. Thus, even with higher values of  $F_{t,h}$  and thus  $F_A$  noticeable savings in direct operating cost could still be obtained.

Although not presented in the curves, if the alternate method of carrying liquid hydrogen at the normal boiling condition is used, the savings in direct operating cost using \$0.50 per pound liquid hydrogen is reduced to 6.0 percent and that using \$0.05 per pound liquid hydrogen is reduced to 10.6 percent.

The aircraft performance for a given high-energy reserve replacement with an  $F_m$  or  $F_{r,h}$  different from those presented in the figures can be determined

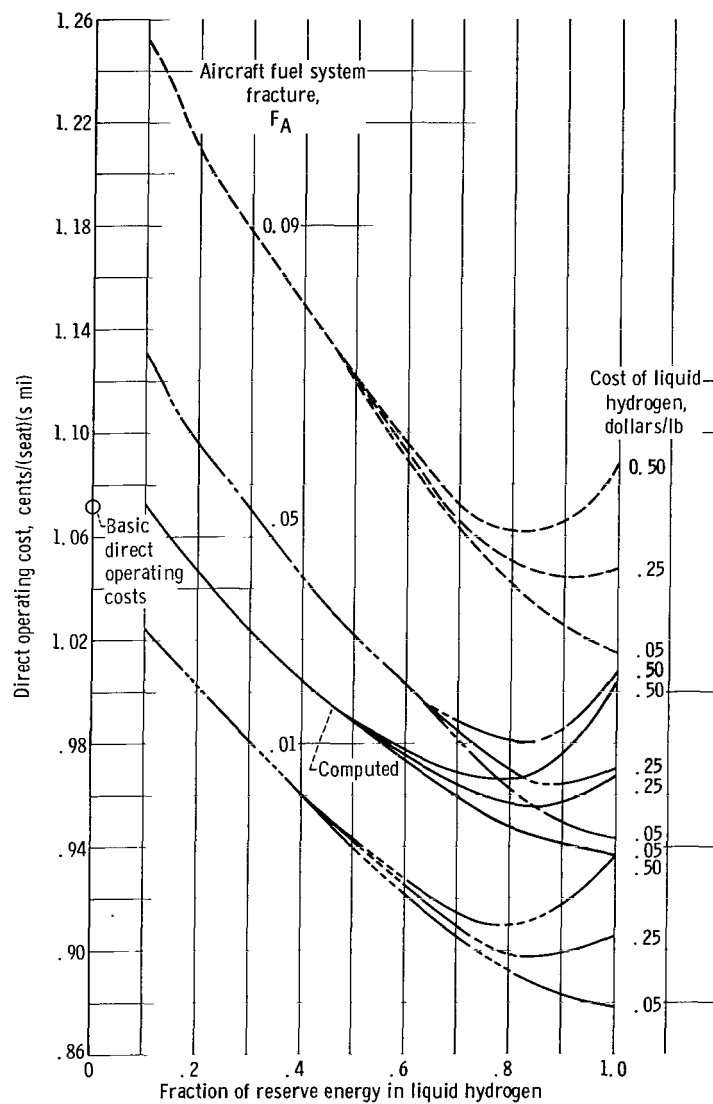


Figure 11. - Direct operating cost for JP-fueled supersonic transport with liquid-hydrogen reserves.

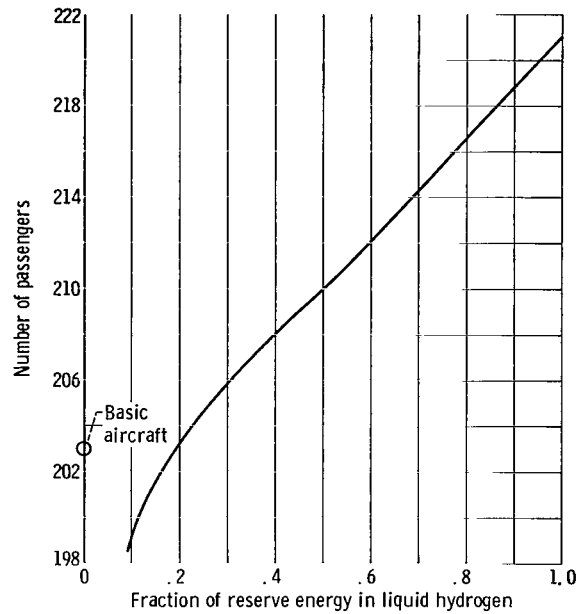


Figure 12. - Number of passengers for JP-fueled supersonic transport with liquid-hydrogen reserve; fuselage extended for all liquid hydrogen added.

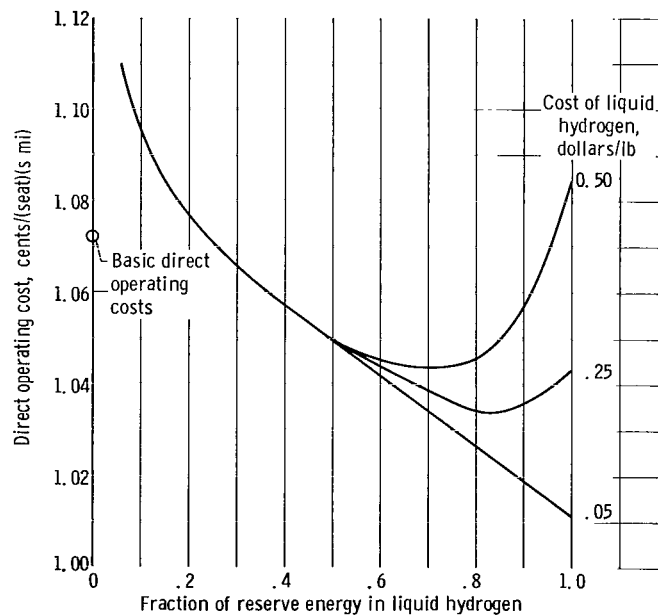


Figure 13. - Direct operating costs for JP-fueled supersonic transport with liquid hydrogen reserves; fuselage extended for all liquid hydrogen.

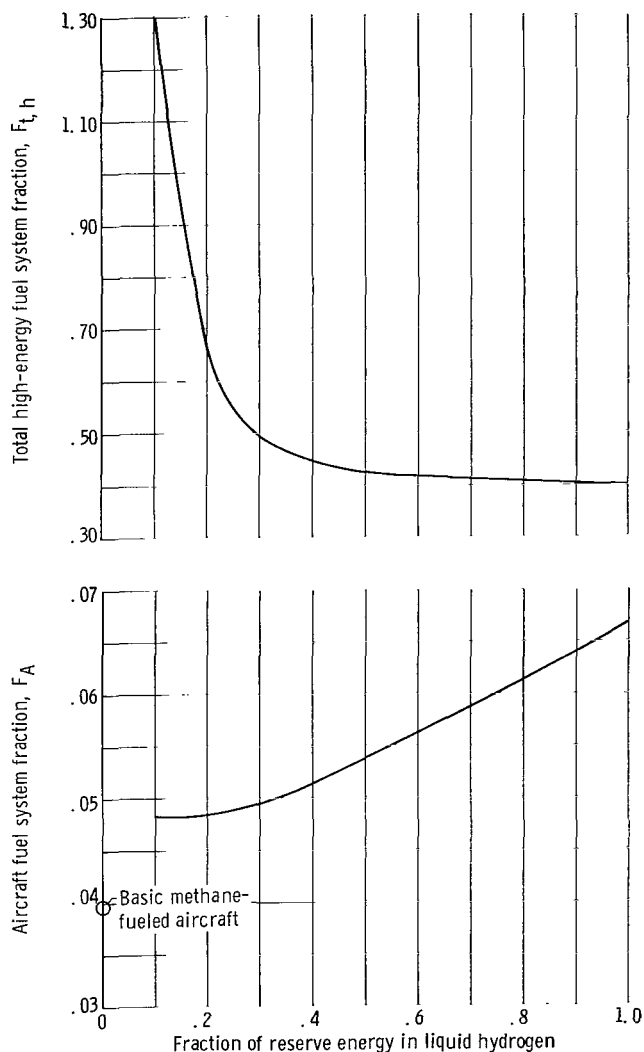


Figure 14. - Computed system fractions for methane-fueled supersonic transport with liquid-hydrogen reserves.

by computing a new  $F_A$  with the use of the weights in table IV (p. 10) and equations (1) and (3). This  $F_A$  can then be used in conjunction with the sensitivity curves to find the desired aircraft performance.

Results of calculations made by assuming that the 27-foot fuselage length of constant cross section and the 5-foot of tapered cross section are not available for liquid-hydrogen storage or passengers are presented in figures 12 and 13. Here the fuselage is extended for all liquid hydrogen added. All other assumptions are the same as in the case just discussed. These results are presented only for the computed  $F_A$ . Figure 12 contains the changes in number of passengers, and figure 13 contains the direct operating cost changes. Figure 12 shows that the increase in passengers is now only 18. Thus, nearly half of the gain obtained by assuming available fuselage liquid-hydrogen storage space is lost. From figure 13 it may be determined that, in the most probable price range of from 0.25 to 0.50 dollars per pound, the maximum direct operating cost savings is only about 3 percent. This case, however, with the extended fuselage is actually a limit, since there is empty volume in the wings of the JP aircraft. Should there actually be no

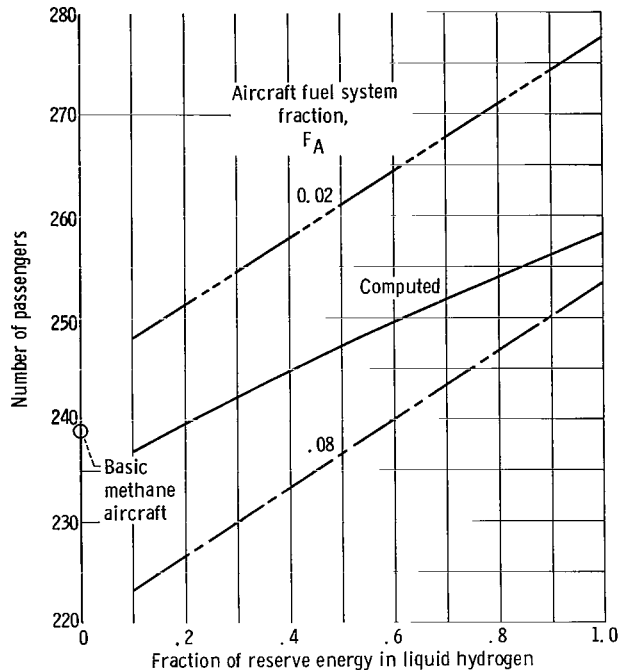


Figure 15. - Number of passengers for methane-fueled supersonic transport with liquid-hydrogen reserves.

empty fuselage the wings could be utilized. The results might be less appealing than in the case in which considerable fuselage length is available because the wings will require higher insulation weights due to their thin cross section and heavier tank weights to hold a pressure of 12.2 pounds per square inch. The gains would be greater than this boundary case, however, since the aerodynamic friction drag and fuselage structural weights would be less.

Figures 14, 15, and 16 refer to a supersonic transport with methane as the main fuel and liquid-hydrogen as the reserve fuel. The methane-fueled aircraft presented in reference 1 is used. Figure 14 shows that the  $F_{t,h}$  for all reserves in liquid hydrogen is 0.398. Methane requires more volume than does JP fuel. Therefore, some methane is stored in the previously mentioned 32 feet of empty fuselage, and thus, some of this space is not available for liquid-hydrogen storage. From the number of passengers of figure 15 and the direct operating costs of figure 16, the fractional gains shown by the computed  $F_A$  curves are seen to be about the same as those of the lengthened fuselage JP-fueled aircraft with liquid-hydrogen reserves. The smaller difference in specific impulse between methane and liquid hydrogen combined with the necessity of increasing fuselage length make liquid-hydrogen substitution appear far less attractive for the methane-fueled aircraft than for the JP-fueled aircraft.

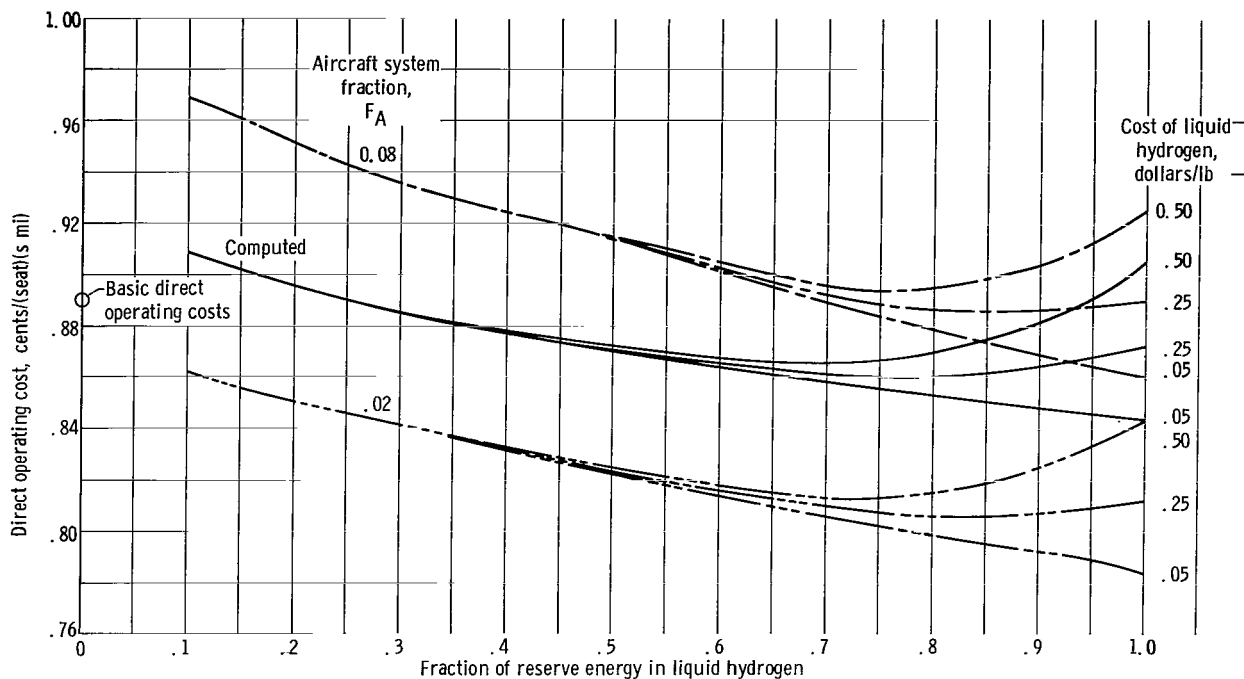


Figure 16. - Direct operating cost for methane-fueled supersonic transport with liquid-hydrogen reserves.

## Improvement Using Ethyldecaborane

Figures 17 and 18 present the number of passengers and the direct operating cost, respectively, for a JP-fueled aircraft with ethyldecaborane reserves. As in the case of

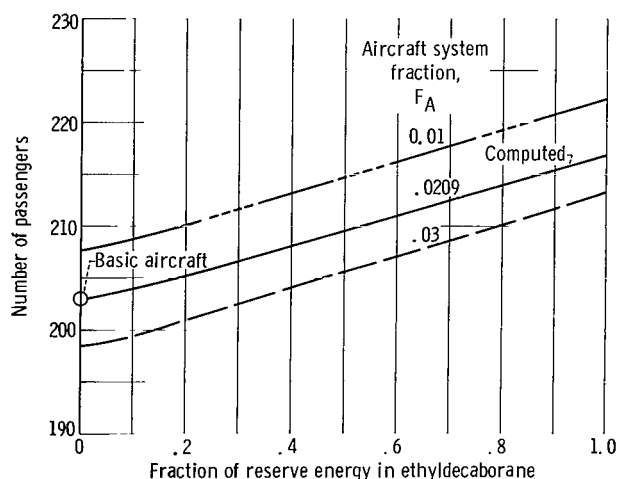


Figure 17. - Number of passengers for JP-fueled supersonic transport with ethyldecaborane reserves.

liquid hydrogen, the maximum number of passengers occurs with total replacement of the JP reserves. The aircraft system fraction  $F_A$  using ethyldecaborane is a constant 0.0209 as in the case of JP, and the curves computed by using this number are discussed. The maximum passenger increase from figure 17 is 14, or 6.9 per cent. From figure 18, however, the maximum decrease in direct operating cost, which occurs with about one-half of the reserve energy in ethyldecaborane, is seen to be small.

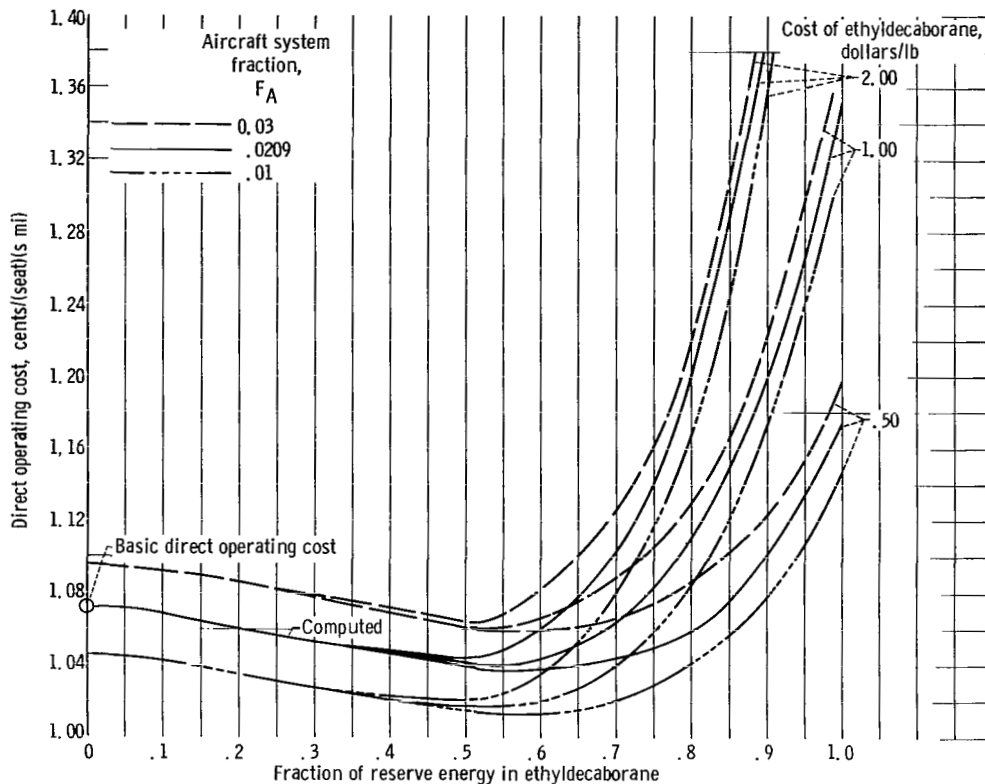


Figure 18. - Direct operating cost for JP-fueled supersonic transport with ethyldecaborane reserves.

This decrease is only a trifle over 3 percent even at the extremely optimistic assumed price of 50 cents per pound, a price far lower than recent cost estimates that run as high as \$20 per pound. Since additional adverse effects due to boric oxide depositions would further degrade this result, this fuel obviously offers no significant operational benefits.

### Improvement Using Methane

The use of methane for reserve fuel in JP-fueled aircraft is presented in figures 19, 20, and 21. While figure 19 presents the computed  $F_A$  and  $F_{t,h}$ , figure 20 presents the number of passengers, and figure 21 shows the direct operating cost. From figures 19 and 20, the maximum passenger increase is determined to be about 3 percent, and it occurs with the total replacement of reserves by methane with  $F_{t,h} = 0.564$  and  $F_A = 0.0264$ . Since the price per pound of methane is close to that of JP fuels, the minimum direct operating costs occur when all reserves are methane; furthermore, the reduction in direct operating cost is just about that of the passenger increase, which is very modest.

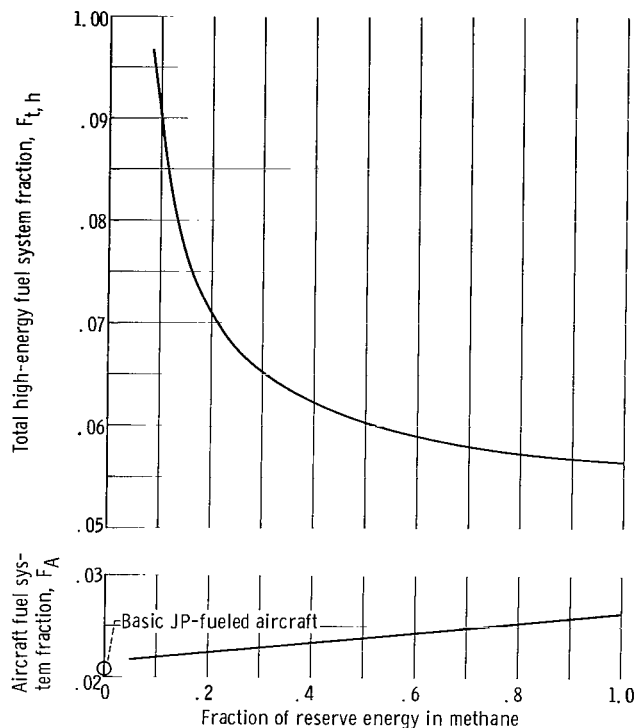


Figure 19. - Computed system weights for the JP-fueled supersonic transport with methane reserves.

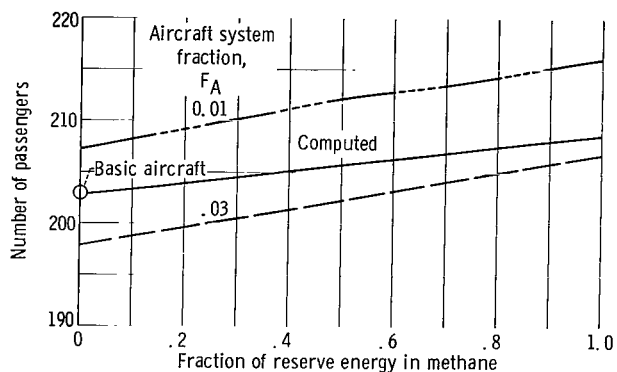


Figure 20. - Number of passengers for JP-fueled supersonic transport with methane reserves.

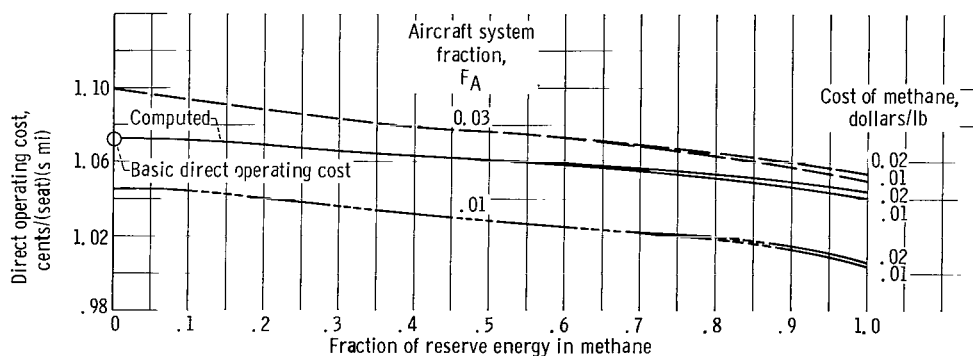


Figure 21. - Direct operating cost for JP-fueled supersonic transport with methane reserves.

If the aircraft is designed for methane reserves and if the price of methane is actually cheaper than JP, then a larger direct operating cost gain can be achieved by burning the methane as mission fuel and keeping part of the higher cost JP main fuel for reserves. If, for example, the price of methane is 0.01 dollars per pound, then the direct operating cost would drop an additional 0.035 cents per seat per statute mile by using the methane reserves in this manner, and the fractional reduction in direct operating cost would be 0.0614 rather than the 0.0288 gain obtained by using the methane only as reserve fuel.



## Improvements Using Ethyldecaborane for Extended Range

The preceding sections have dealt with the effort to improve airplane performance at the design range. The case is now considered where the nominal design performance of the JP-fueled aircraft is presumably adequate, but it is desired to apply the airplane to longer range missions. The longer range is accomplished by reducing the passenger load and by adding an equal weight of fuel. However, the aircraft in this single instance is assumed capable of holding the extra fuel, and the seats are not removed. Thus, the aircraft remains constant in empty weight, takeoff gross weight, and size.

The improvements obtained by using ethyldecaborane for extended range are presented in figures 22 and 23. In figure 22 the abscissa is the range beyond the design range in statute miles, and the ordinate is the number of passengers. The curves for all JP, JP reserve completely replaced by ethyldecaborane, and ethyldecaborane substitution for minimum direct operating cost are presented. At the design range of 3500 nautical miles, or 4030 statute miles (e.g., New York to Berlin), the all JP-fueled supersonic transport carries 203 passengers. For the flight from New York to Rome, 336 miles beyond the design range, the all JP aircraft can carry only 160 passengers. Using ethyldecaborane for reserves in an amount that minimizes the direct operating cost for an ethyldecaborane price of 2.00 dollars per pound yields a gain of 16 passengers, or

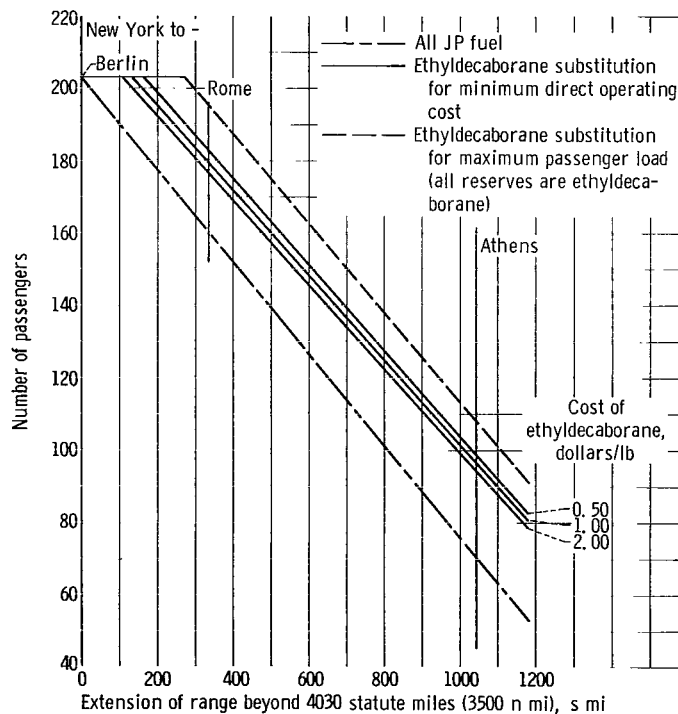


Figure 22. - Number of passengers for JP-fueled supersonic transport at extended ranges.

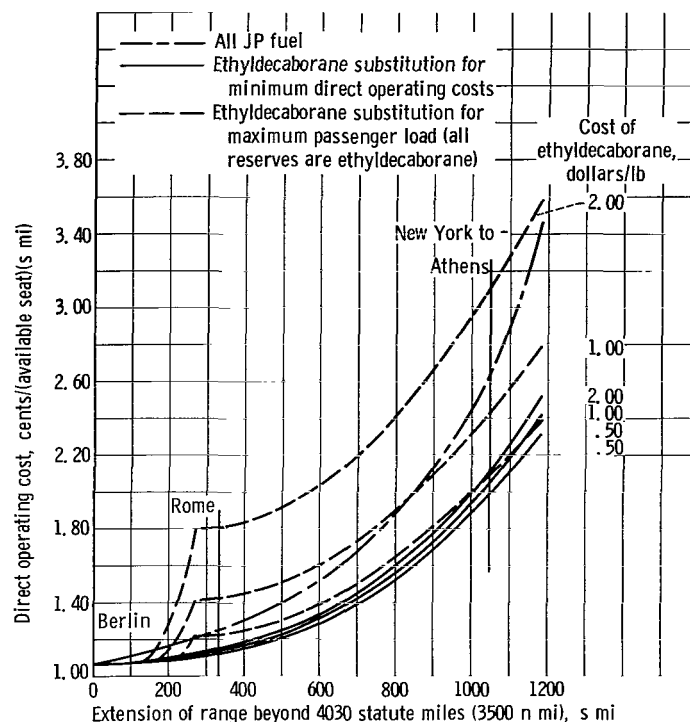


Figure 23. - Direct operating cost for JP-fueled supersonic transport at extended ranges.

10 percent. A 21 percent passenger increase is possible if all the reserves are in ethyldecaborane. The percent gains are larger at the longer range extensions, for example, from New York to Athens.

The ordinate of figure 23 is in cents per available seat per statute mile. Here the direct operating cost on the New York to Rome trip is 1.26 cents per available seat - statute mile with all JP fuel and only 1.16 cents per available seat per statute mile with ethyldecaborane priced at 2.00 dollars per pound. Although this is a savings of nearly 8 percent, it is still much higher than the 1.072 cents per seat mile for the all-JP-fueled aircraft flying the design range. Thus, if extended range flights are required, ethyldecaborane reserves could reduce the resulting increase in direct operating cost while increasing, with only minor aircraft modifications, the number of passengers carried.

## CONCLUDING REMARKS

This analysis, based on the statistical frequency with which reserves are used, has shown (as summarized in tables VIII and IX, pp. 20 and 21, respectively) that high-energy fuels, even though costly, can improve supersonic transport economics. The

magnitude of these gains is a function of the reserve that the aircraft is forced to carry by regulation, however, and a major reduction in The Federal Aviation Agency requirements, although unlikely, would substantially reduce these gains. The outstanding case is that of liquid hydrogen used in the JP-fueled aircraft. Both the increase in number of passengers and the reduction in direct operating cost appear very attractive. Note, however, that to achieve these improvements in direct operating cost with liquid-hydrogen reserves, the boiloff must be essentially eliminated. This elimination of boiloff appears feasible by subcooling the liquid hydrogen and by using insulation. A question arises as to the safety of liquid hydrogen. Liquid hydrogen, however, has already been chosen for use in manned space flight, and it is the projected fuel for hypersonic aircraft. Therefore, it is quite probable that the dangers associated with the use of liquid hydrogen can be minimized by technical advances.

Using ethyldecaborane as a reserve fuel yields only a small reduction in direct operating cost. Since the expected reduction in engine performance caused by the boric oxide deposits is ignored even in obtaining these modest improvements, the use of this fuel does not appear at all attractive.

An aircraft using high-energy fuels only for reserves has one advantage over an aircraft using high-energy fuels also as mission fuel. Since the mission fuel is still the more conventional JP fuel, should it ever be required, the aircraft could be operated usefully between airports where high-energy fuels are not obtainable. The number of passengers or the range would be reduced in such a case, but use of the aircraft would still be possible.

The idea of high-priced, high-energy fuel being substituted for low-priced, low-energy fuel for the reserves is not necessarily limited to supersonic transport applications. In any vehicle in which the reserves are sizable, seldom used, and recoverable, this substitution would very probably result in gains in performance and direct operating cost. Indeed, although the low level of current and expected direct operating costs do not make it seem appealing, even the subsonic aircraft could benefit by using this high-energy-reserve replacement concept.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, October 26, 1966,  
126-15-02-02-22.

## REFERENCES

1. Whitlow, John B., Jr.; Eisenberg, Joseph D.; and Shovlin, Michael D.: Potential of Liquid-Methane Fuel for Mach 3 Commercial Supersonic Transports. NASA TN D-3471, 1966.
2. Dommasch, Daniel O.; Sherby, Sydney S.; and Connolly, Thomas F.: Airplane Aerodynamics. Second Ed., Pitman Publishing Corp., 1957.
3. Stickle, Joseph W.: Consideration of Fuel Requirements for Supersonic Transport Operation. Conference on Aircraft Operating Problems. NASA SP-83, 1965, pp. 193-202.
4. Anon.: Request for Proposals for the Development of a Commercial Supersonic Transport. Federal Aviation Agency, Aug. 15, 1963.
5. Anon.: Liquid Hydrogen Technology. Rep. No. AE 62-0774, General Dynamics/Astronautics, Sept. 1962.
6. Vance, R. W.; and Duke, W. M., eds.: Applied Cryogenic Engineering. John Wiley and Sons, Inc., 1962.
7. Anon.: Recent Hef-3 Property Information. Descriptive Data 2709, Beech Aircraft Corp., Mar. 17, 1959.
8. Pusanski, Barbara: Self-Ignition Temperatures and Flash Points of Some High-Energy Fuels. NACA RM E56C16a, 1957.
9. Hall, Eldon W.; and Weber, Richard J.: Tables and Charts for Thermodynamic Calculations Involving Air and Fuels Containing Boron, Carbon, Hydrogen, and Oxygen. NACA RM E56B27, 1956.
10. Perry, John H., ed.: Chemical Engineers' Handbook. 4th ed., McGraw-Hill Book Co., Inc., 1963.
11. Hald, Anders: Statistical Theory, with Engineering Applications. John Wiley and Sons, Inc., 1952.
12. Anon.: Standard Method of Estimating Comparative Direct Operating Costs of Transport Airplanes. Air Transport Association of America, June 1960.
13. Anon.: Santocel A- Monsanto's Silica Aerogel for Efficient Thermal Insulation. Tech. Bull. I-180, Monsanto Chemical Co., Oct. 1959.
14. Anon.: Dupont H Film - Summary of Properties. Bulletin H-1, E. I. DuPont de Nemours and Co., 1965.

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